

LANDFORM EVOLUTION AND FORMATION OF FERRICRETE DURICRUSTS, EL HEIZ AREA, EL BAHARIYA DEPRESSION, WESTERN DESERT, EGYPT

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Two main types of ferricrete duricrust are recognized in El Bahariya depression; one is high-lying and the other is low-lying. The first type forms a distinctive morphologic marker of fairly constant altitude and thickness, capping the summits of isolated cone-hills, inselbergs and flat-topped tablelands of different stratigraphic units, i.e. Bahariya Formation (Early Cenomanian), El Heiz Formation (Late Cenomanian), El Hefhuf Formation (Campanian) and Naqb Formation (Middle Eocene). It denotes together with silcrete and calcrete remnants of an old continuous erosion surface, that was formed by general lowering of the landscape over a long period of humid climate (most probably during the Oligocene-Miocene? time). The second ferricrete type appears to be genetically related to subsequent etchplanation and pedimentation processes (post Miocene-Quaternary), that acted upon the old erosion surface and the related duricrust and suggest to be responsible for the excavation of El Bahariya depression, through: 1) incision of the valleys; 2) destruction and stripping of the old duricrust; 3) stripping of the lateritic regoliths formed beneath the old erosion surface; 4) slope retreat, scarp retreat and formation of isolated landforms, and 5) pavementation, pedimentation and formation of younger erosion

surface. This ferricrete type occurs as bench-like form demarcating breaks within retreating slopes or as thin cap mantling the pediments and the floor of the depression.

Kind and magnitude of structures in the area are of prime importance in facilitating the progress of the morphologic processes

INTRODUCTION

The aim of this work is to present some new observations that may help understanding the nature and mode of formation of the ferruginous sediments (the Oligocene Radwan Formation, El Akkad and Issawi, 1963) of El Heiz area (Fig. 1), and to elucidate their genetic relation with the morphologic development of El Bahariya depression.

These rocks were previously described as very hard ferruginous, silicified grits and quartzite with limonitic material of Oligocene age, either of lacustrine origin (Ball and Beadnell, 1903; Hume, 1909; El Akkad and Issawi, 1963; and Said and Issawi, 1964), or of hydrothermal (replacement) origin (Amer, 1968 and 1973; Basta and Amer, 1969 a,b,c and d, Awadallah *et al.*, 1984 a,b and Shaalan *et al.*, 1984). Zaatout (1958) and El Shazly (1962) related the low grade ore of El Heiz area to chemical weathering and replacement of the original quartz grains. Agthe (1985) and Mücke and Agthe (1988) described these ferruginous sediments as continental red beds formed during the Cretaceous-Tertiary transition.

Three main genetic models were postulated for the origin of El Bahariya depression as well as the other depressions of the Western Desert, namely: 1) sculpturing by wind erosion during the Pleistocene-Holocene time (Ball, 1927, 1933; Sandford and Arkell, 1929; Peel, 1941; Knetsch and Refai, 1955); 2) tectonic origin (Beadnell, 1905; Hume, 1925; Ibrahim, 1956; Knetsch and Yallouz, 1955 and Murray, 1951), and 3) tectonic and wind action (Omara, 1952 and Saad, 1979). The regional lineation pattern and faults of the Central Western Desert proved to control, to a substantial degree, the shapes of the Siwa, Bahariya and Farafra depressions (El-Etr, 1977 and El-Etr and Moustafa, 1978). Recently, El Aref and Lotfy (1985); El Aref *et al.*, (1987); Hassan (1987); Abu Khadra *et al.*, (1987) and Lotfy (1988) referred to the role of multi-erosion cycles, involving karstification, in the landform evolution of the Western Desert and the formation of El Bahariya and El Farafra depressions.

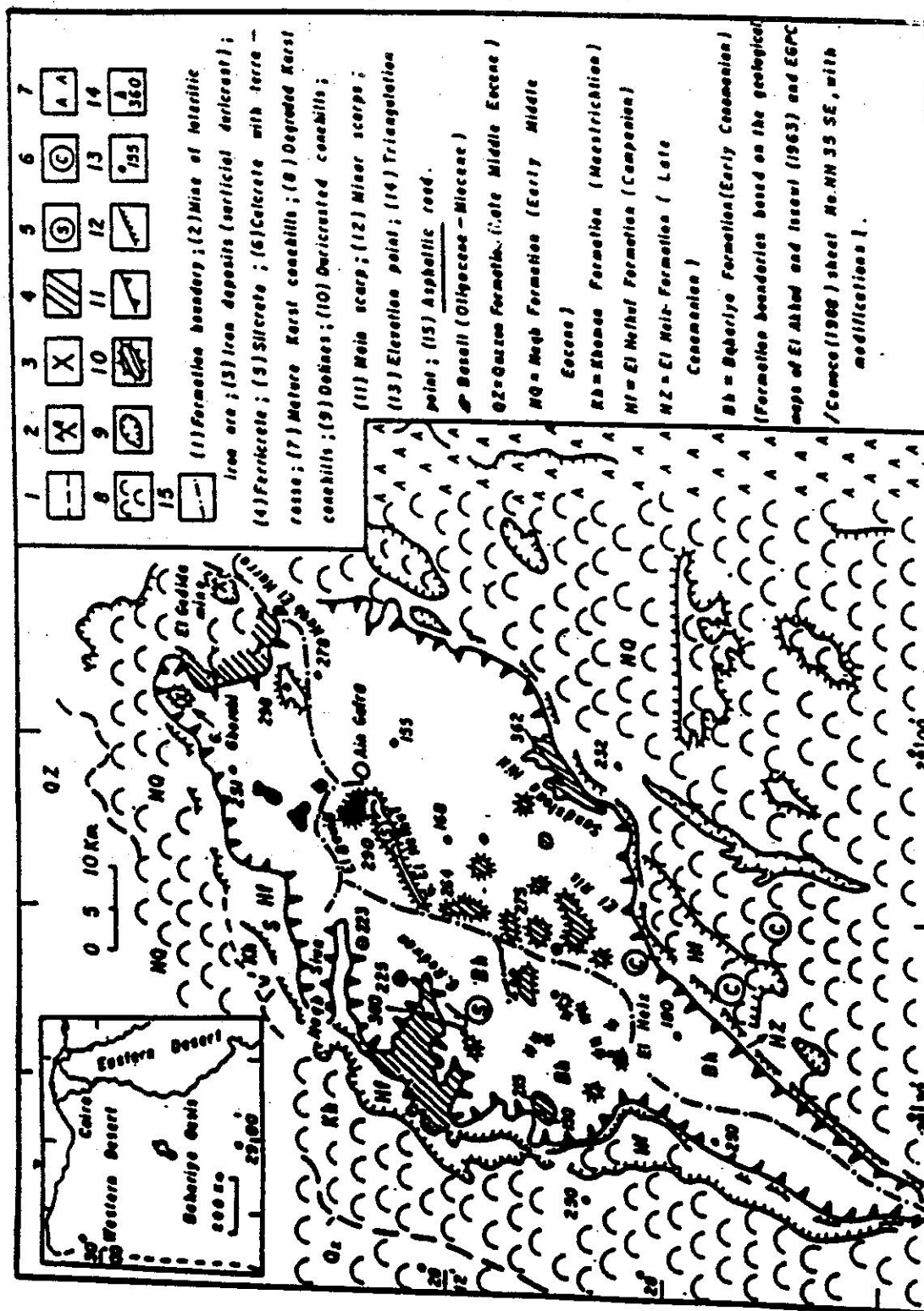


Figure 1: General geomorphologic map of El Bahariya depression

The present work is based on field, stratigraphical, structural and mineralogical studies as well as morphometric analysis. A general morphologic map of El Bahariya region, a detailed morphologic map of El Heiz area and representative vertical and lateral geologic profiles are presented. The structure of El Heiz area is studied using aerial photographs (scale 1:20,000) and augmented by field observations and measurements.

LITHOSTRATIGRAPHY

The stratigraphy of the exposed rocks of El Bahariya region can be expressed by the stratigraphic units shown in Table 1, based on the classifications of El Akkad and Issawi, 1963; Said and Issawi, 1964 and the Geological map of Egypt EGPC/Conoco sheet No. NH 35 Bahariya, 1988, with modifications.

The floor of El Bahariya depression consists of the clastic rocks of the Bahariya Formation. The main scarps, the inselbergs and cone hills within the depression are formed of the Bahariya Formation which may be overlain by either El Heiz, and El Hefhuf or the Naqb Formations (Fig. 1). The karstified Cretaceous and Eocene rocks built up the plateau.

The well defined and accepted Oligocene deposits of El Bahariya region are those of Qatrani Formation of the northeastern plateau (Strougo and Hottinger, 1987; Bown and Kraus, 1988 and the Geological map of Egypt, sheet No. NH 35 SE, Conoco, 1988). These sediments were considered previously as Radwan Formation (El Akkad and Issawi, 1963 and others). They represent the southwestern extension of the Oligocene Qatrani Formation of G. Qatrani, El Fayum, and cover Qasr El Sagha (Late Eocene - Early Oligocene) and El-Hamra (Late Eocene) Formations. The rocks of this formation are completely different from the ferruginous succession of the so called "Radwan Formation" described at its type locality of G. Radwan. The units of Qatrani Formation represent deposition under channel fluvial environment, as they consist of repeated fining upward sequences of cross-bedded conglomerate, gravelly sandstone, siltstone and mudstone with common intraformational mudstone clasts and wood debris along the basal part of each sequence. According to the results of the present work, the ferruginous sediments of "Radwan Formation" represent the products of deep weathering processes that acted upon different rock units of Cretaceous and Eocene age. Therefore, it is preferable here to use the term Qatrani Formation for the typical fluvial

Age	Formation/ Unit	Lithology/characters
Quaternary		bench-like and pediment ferricretes ; lag and playa deposits ; mud flows ; salt lakes ; sand dunes and sheets ; sand linear ridges (seif).
Miocene (?)		
Miocene (?)	lateritic iron deposits and surficial duricrusts/fluvial deposits of Qatrani Fm.	accumulation of lateritic iron deposits in El-Gedida area, development of in situ deep weathering profile of G. Ghorabi, up to 19 m thick, and surficial duricrusts in El Heiz area, 6-16 m ; northwards of El Bahariya depression, deposition of channel sediments (Qatrani Fm.) took place.
Oligocene	Volcanic rocks	basalt dykes and sills.
----- unconformity -----		
Late Eocene to Late Middle Eocene	Qasr El Sagha Fm.	fossiliferous limestones, sandstones,
	El Hamra Fm.	fossiliferous limestones, sandy and glauconitic with intercalations of clays and sandstones.
Late Middle Eocene	Qazzun Fm.	nummulitic limestones and dolostones, white in colour ; the exposed rocks are highly karstified, spherodially weathered, recrystallized, dedolomitized and silicified, mouldic cavities are common; surficial calcrete crusts.
Early Middle Eocene	Naqb Fm.	nummulitic dolostones and limestones. The exposed rocks show characteristic cone karst landforms with solution openings and intrakarstic sediments; the rocks are pink to violet, brecciated, cavernous, recrystallized, dedolomitized, ferruginated and silicified ; mouldic cavities and ferricrete and silcrete surficial crusts are common.
----- unconformity -----		
Maestrichtian	Khoman Fm.	chalks and chalky limestones forming karst cone hills with calcrete deposits.
Campanian	El Hefhuf Fm.	bedded fossiliferous cherty dolostones, phosphatic within its lower part, the exposed rocks are highly karstified, brecciated, dedolomitized and silicified with surficial crusts of silcrete and ferricrete.
----- unconformity -----		
Late Cenomanian	El Heiz Fm.	three members, a lower sandy dolostone, a middle clastic and an upper sandy dolostone member. The rocks are highly karstified and the exposed surfaces of these members are covered by different types of surficial duricrusts (ferricrete, calcrete and silcrete).
----- unconformity -----		
Early Cenomanian	Bahariya Fm.	fluviomarine clastic successions of cross bedded sandstone, siltstone, mudstone and shale; intercalations of ironstone bands, laminae and concretions within its upper and lower parts; the exposed rocks are mantled by ferricrete.

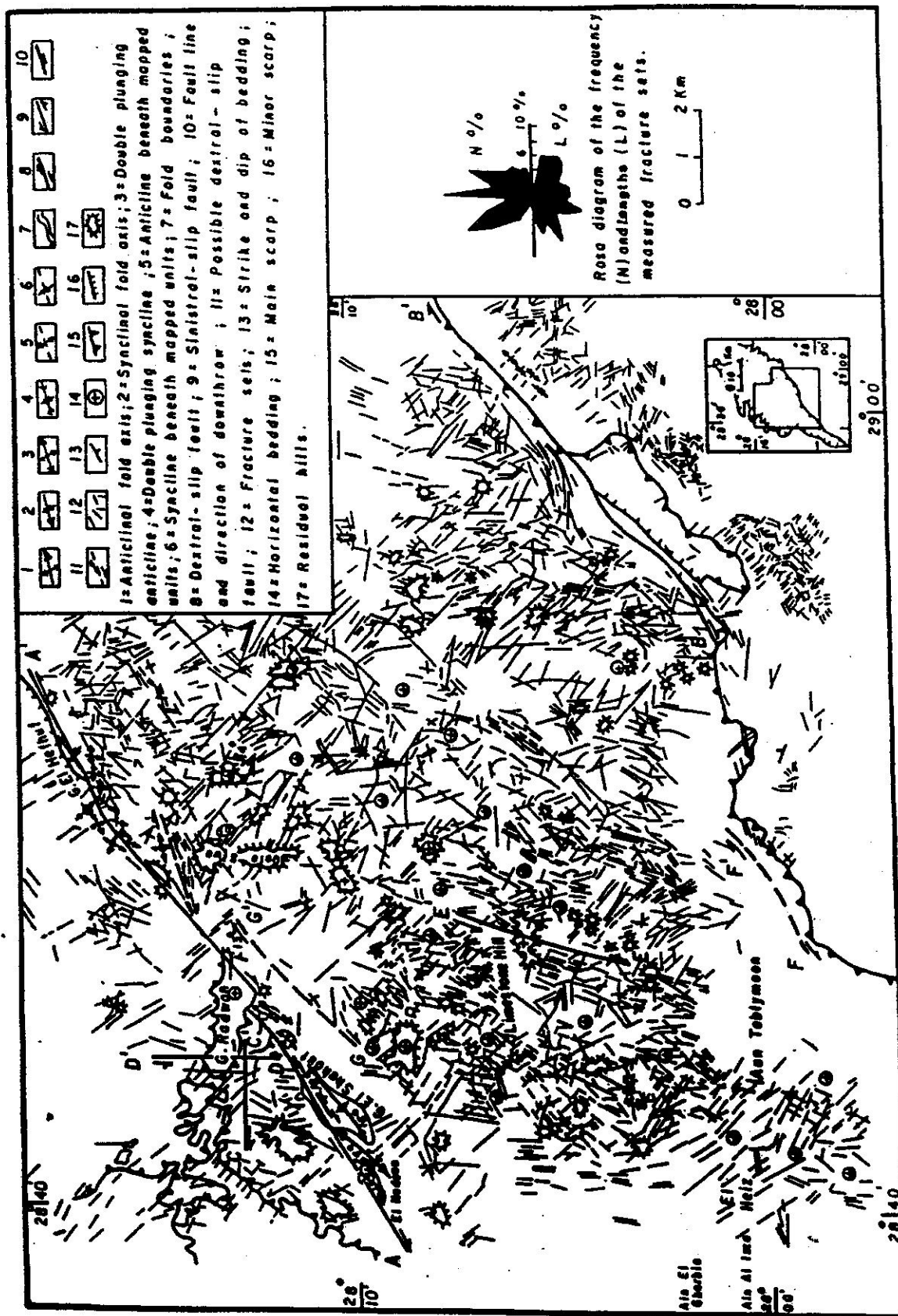


Figure 2: Structural map of El Heiz area.

Oligocene succession of the northeastern plateau instead of "Radwan Formation". Accordingly, it is recommended that the term "Radwan Formation" used in El Bahariya depression be omitted.

STRUCTURE OF EL HEIZ AREA

This area is characterized by frequent development of faults and folds of different styles and trends (Fig. 2). The presence of the previously described major anticlines of El Heiz, Radwan, El Ris and Sandstone Hill (El Akkad and Issawi, 1963) could not be confirmed in the field. The beds within and around these areas are found to be mostly horizontal with slight disturbance near the fault contacts or they are nearly parts of mesoscopic folds associated with master strike-slip faults. The area is dissected by NE, NW, N-S and E-W faults and associated fracture sets. The master A-A', B-B', C-C', D-D', and E-E' faults (Fig. 2) have evident horizontal slip component. The structural pattern around both sides of the master strike-slip faults (A-A', B-B') is quite different and slickensides of low rake angle are common. The folds are represented by a group of en echelon alternating anticlines and synclines, either of plunging or double plunging types and closely associated with the NE master strike-slip faults (A-A', B-B', Fig. 2, Pl. 1a). The fold axes make an obtuse angle with the fault traces. The folds are asymmetrical with steep limbs facing to the associated faults and gradually changed into open folds away from the faults. Different stratigraphic units were affected by these folds, i.e., Bahariya, El Heiz and El Hefhuf Formations.

The en echelon arrays of the folds in association with the master strike-slip faults indicate simple shear mechanism (Jamison, 1983). According to Wilcox *et al.* (1973), this type of folds appears to be developed in response to a deep seated shearing and succeeded by the generation of the surface strike-slip faults. The development of some of these folds in double plunging form and the variation of the rock units forming the shell of the folds, where the intensity of folding is usually increased in the older stratigraphic units, indicate multi-phases of deformation accompanied with the rejuvenation of the deep seated shearing.

MORPHOLOGIC LANDFORMS, PALEOEROSION SURFACES AND RELATED SURFICIAL DURICRUSTS

As shown in Figure 1, El Bahariya region can be classified into three main morphologic units: a) karstic plateau; b) main scarp, and c) surficial duricrusts, paleoerosion surfaces and etchplains (including the main depression).

1. Karst Plateau

The present topographic surface of the plateau is actually a karst surface, dominated by cone karst landforms, together with filling features (caves, cavities and channels), solution depressions (dolines) and surficial deposits (terra-rossa, ferricrete, silcrete and calcrete). The karst profile is extended downwards until the contact with the Bahariya Formation.

The karst morphology grades from mature and degraded cone karst down to plained areas, similar to those described by El Aref *et al.* (1987) in the northeastern plateau of the depression. The mature cone karst consists of highly elevated and closely spaced conical hills, up to 40 m high and 50 m in diameter, separated from each other by narrow and deep V-shaped depressions (cockpits). Directed cone karst type and karst linear ridges of irregular peaks are also common (Pl. 1b). The summits of the mature cone hills have the same elevation of the tops of the duricrusted isolated landforms occurring within El Bahariya depression. The Karst cones show noticeable reduction in their elevation and diameter towards the main depression and the occasionally distributed dolines. The degraded cockpits consist of widely spaced cone hills smaller than those of the mature cockpits, up to 20 m high and 20-40 m in diameter. The hillside slopes range between 25° to 30°. Solution depressions (dolines) of oval or elongated shapes, up to 30 m in diameter, are frequently distributed within the degraded cone karst terrains. Larger solution depressions (poljes) with flat floors, up to several kilometers long and up to 3 km wide, are also present. The solution depressions are separated from the surrounding cone hills by minor escarpments, up to 15 m high. They may include isolated cone hills having the same elevations of the bases of the surrounding cone hills. The floors of these depressions have different elevations ranging from 175 to 225 m a.m.s.l. Some dissected flat-topped tablelands, up to 2 X 10 km, are also present. These tablelands are sharply outlined by erosional escarpments characterized by the occurrence of irregular embayments with gradual dislocation into small peaks or hillocks and development of solution features along the free faces of the escarpments. Such solution features are manifested by: a) the occurrence of down cutting or foot recesses; b) flaking, consisting of small flakes of rocks, being dislodged from the free faces of the escarpments and accumulated on the floor of the recesses, c) granular disintegration of the carbonate rocks, and d) scaling on the rock faces, where fragments break off parallel to the surface with accumulation of the detrital materials behind the scales.

Around the main scarps of El Bahariya depressions, the carbonate rocks become highly paved and plained with only scattered and less conspicuous cone-hills or rubble cones (Pl. 1b). The bare surfaces are dominated by karren morphogenetic features and characterized by the presence of steps which are guided mainly by different stratigraphic units and diminish gradually towards the main depression, where the older units are successively exposed. The carbonate pavements of El Heiz and El Hefhuf Formations are commonly covered by calcrete with relicts of terra-rossa and (or) silcrete. The plained surfaces of the Naqb Formation are usually capped by ferricrete, especially around the main scarp of the depression.

2. Main Scarp

The main scarp rises to different elevations above the depression's floor, ranging from 50 to 100 m. It exhibits the classical four slope elements of King (1962), i.e., upper convexity, cliff, debris slope and lower concavity (pediment), and separates two erosion surfaces (S1 and S2, Fig. 4). The eastern scarp has a smooth outline with the exception of El Harra indentation. At the area between Naqb Lagalite and Sandstone Hill, the scarp face is completely covered by blown sand. The most striking feature of the western scarp is the occurrence of a number of fan-shaped embayments such as G. Ghorabi, El Tibnia, Naqb Siwa and Naqb Dalla embayments. Smaller stream channels also

Cut into this scarp and the associated pediments. Lateral corrosion by stream floods were probably responsible for the formation of these embayments, where upland valleys debouch into the low lands of the depression. Stream floods appear to be swung laterally and undermined the steep slopes with continuous trimming back of the spurs between the adjacent embayments and retreat of the scarp. This led to the gradual reduction of the upland masses and formation of prominent projections such as El Tibnia promontary or isolated interfluvies such as G. Ghorabi inselbergs, G. El Dist, G. El Maghrafa, and G. Radwan, among others.

3. Surficial Duricrusts, Paleoerosion Surfaces and Etchplains

Duricrust (Dury, 1969), is the term used in the literature for the indurated zone of the typical deep weathering profile (laterite profile). Considering the topographic situation of the laterites or surficial duricrusts, Du Preez (1949 a) referred to high-lying or peniplain laterite and to low-lying or pediplain laterite, which correspond to the widely occurring older laterite and younger laterite in tropical Africa (De Swardt, 1964).

Surficial ferricrete (laterite) deposits have been recorded in the southern part of the Western Desert of Egypt and in the adjacent countries, south and west to Egyptian borders (Sandford, 1935). Ferricrete, silcrete and calcrete are also recorded in the northeastern plateau of El Bahariya depression, (El Aref and Lotfy, 1985, El Aref *et al.*, 1987 and Lotfy 1988). A relatively thick calcrete deposits cover the karstified Cretaceous and Paleocene chalks of El Bahariya-Farafra stretch (Abu Khadra *et al.*, 1987).

In El Bahariya depression, different types of surficial duricrusts are recognized. They are classified into: a highly-lying and a low-lying types.

a. High-Lying Duricrusts

These duricrusts form a horizontal indurated morphologic marker, capping the bevelled summits of residual landforms and the main scarps and well represented in El Heiz area (Figs. 1, 3, 4 and Pl. 1c). They are mostly flat-lying with occasional highs and lows and represented mainly by ferricrete with less abundant silcrete and calcrete. The summits of these duricrusts fall within very narrow altitude range, between 270 and 300 m a.m.s.l. and can be correlated with the deep weathering lateritic profile of G. Ghorabi (El Aref and Lotfy, 1985), which lies at nearly the same altitude, 270 - 310 m a.m.s.l. These high-level duricrusts comprise, together with the underlying weathered rocks, a typical deep weathering profile. Thus, they delineate the level of an old erosion surface (Sl, Fig. 4), that resulted from an old erosion cycle, which acted upon the uplifted Cretaceous and Eocene rocks, under humid paleoclimate, and terminated by arid to semiarid regime. The horizontal strata of the ferricrete duricrust, the common ferricrete type, covers the following rock units: a) the exposed clastic rocks of the Bahariya Formation (Pl. 1c), b) the exposed sandstones of the middle member of El Heiz Formation, and c) the karstified dolostones of El Hefhuf and Naqb Formations (Pl. 1d). The high-

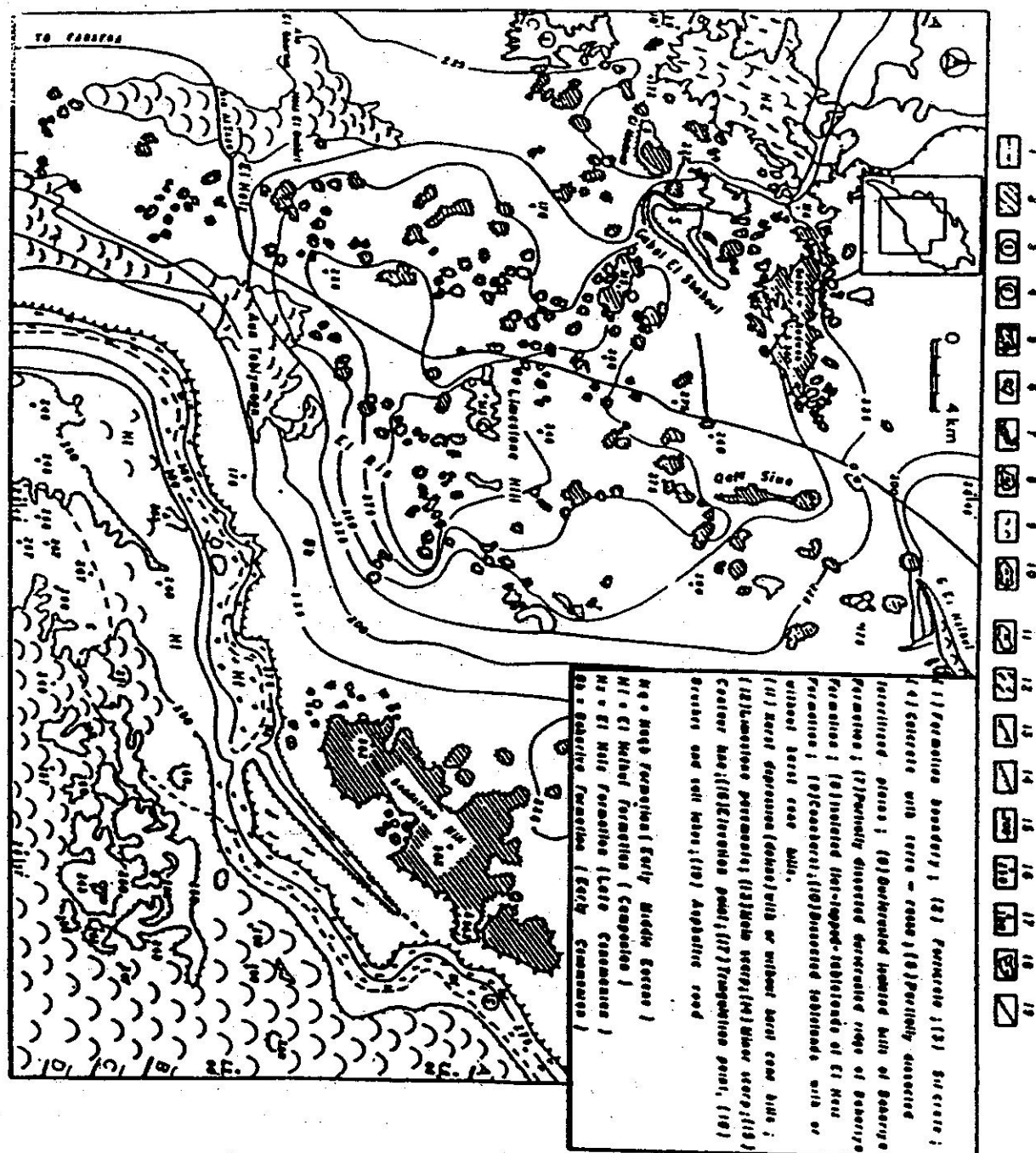


Figure 3: Detailed geomorphologic map of Gabal Radwan - El Heiz area, showing the distribution of the isolated conehills capped by ferricrete duricrust. Formational boundaries based on the geological maps of El Akkad and Issawi (1963) and EGPC/Conoco (1988), sheet No. NH 35 SE, with modifications.

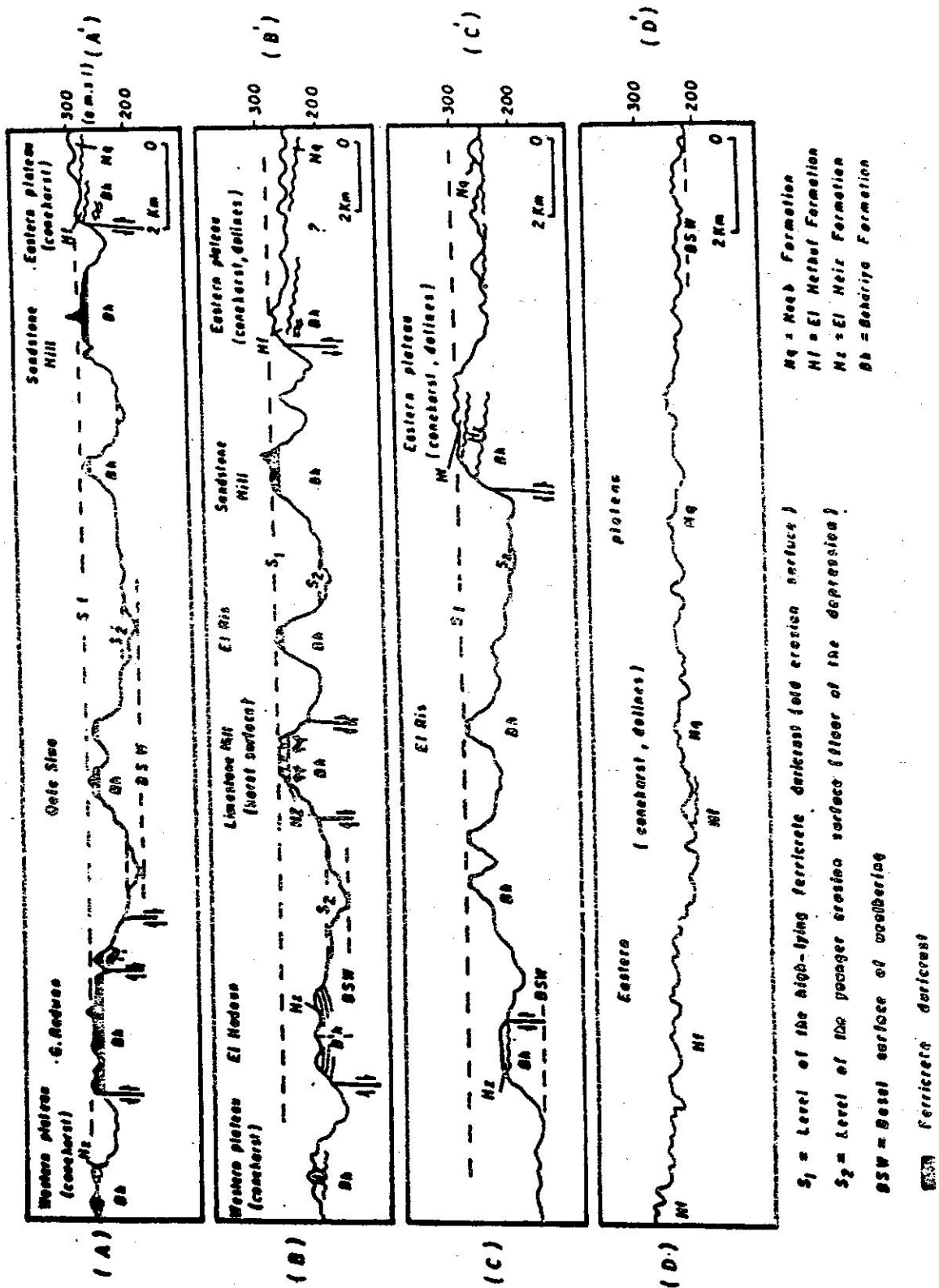


Figure 4: Exaggerated cross profiles (A-A'; B-B', C-C', D-D'). For location see Figure 3.

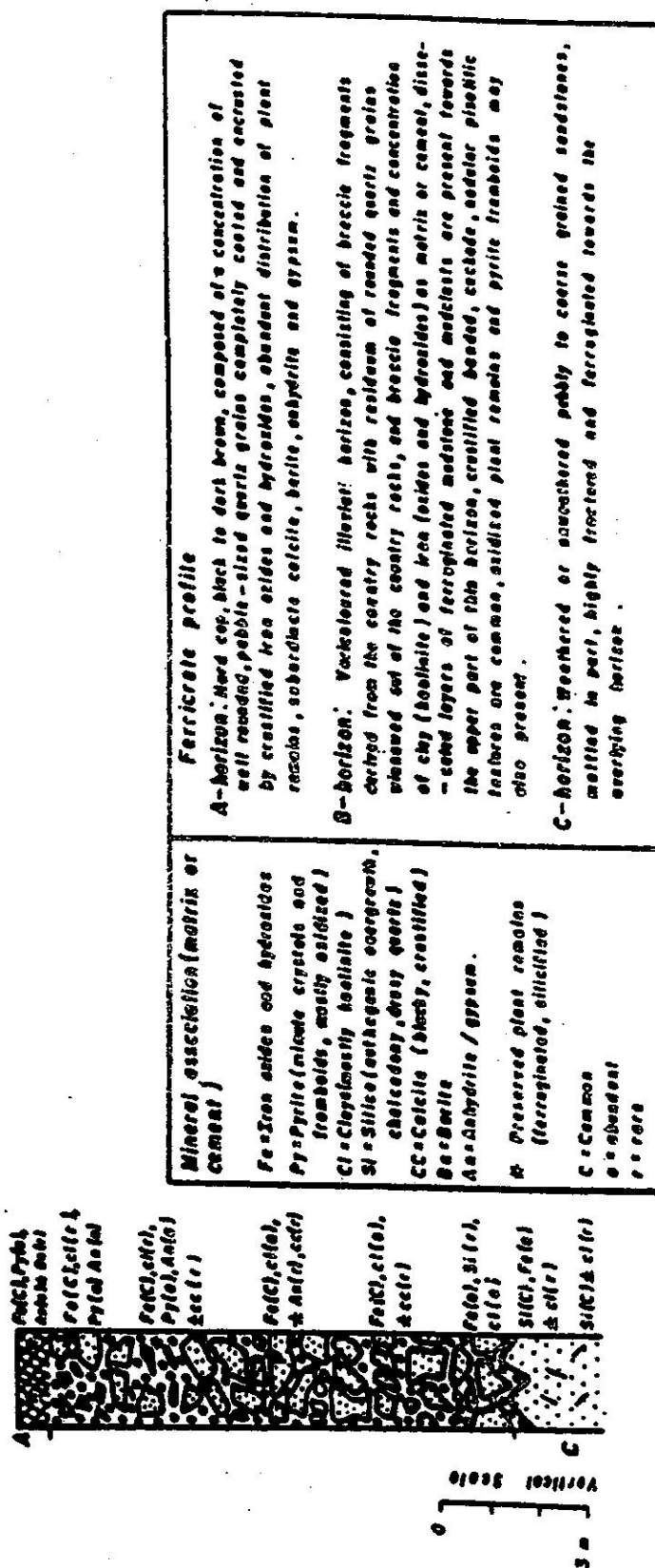


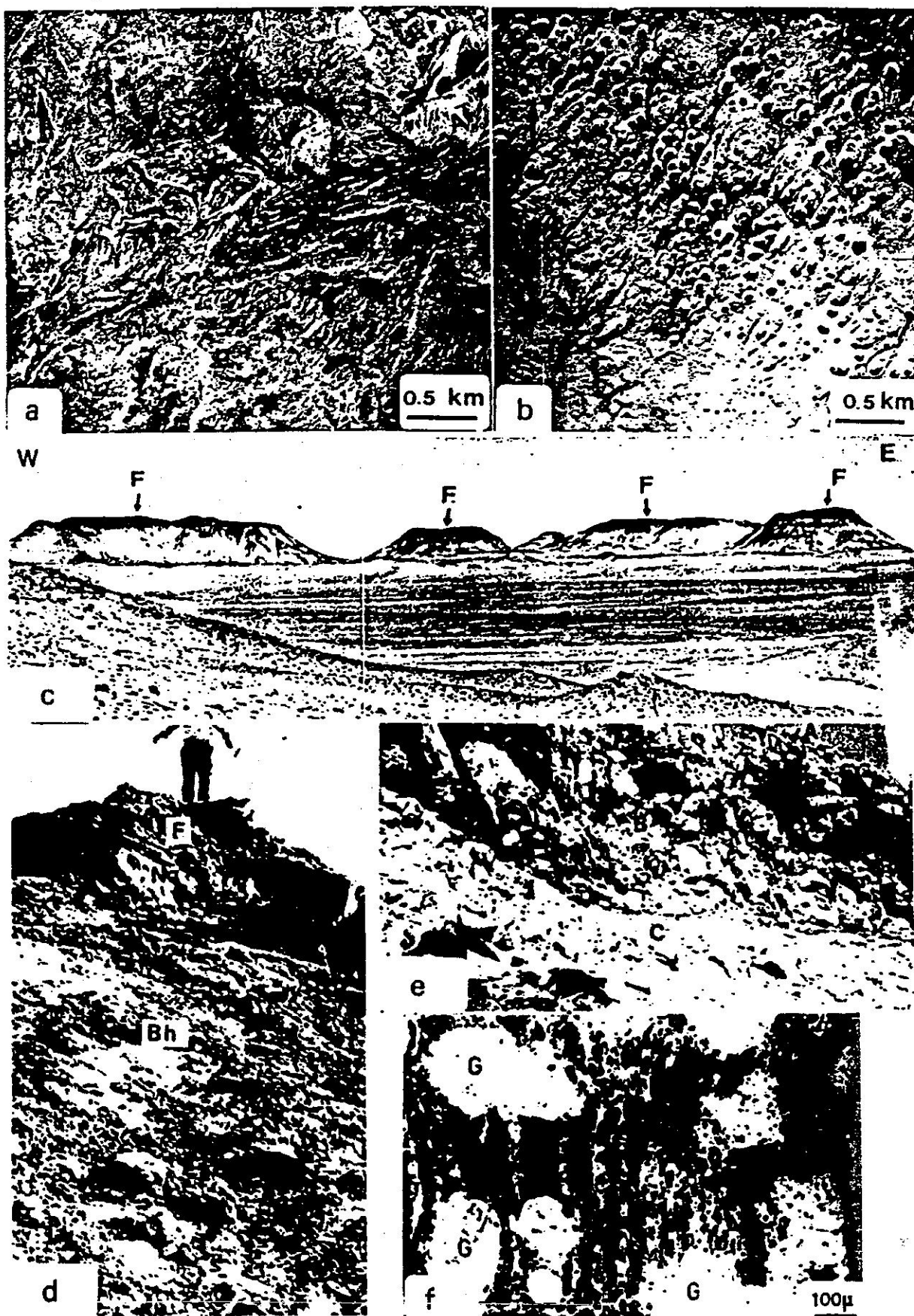
Figure 5: Representative ferricrete profile overlying the Bahariya Formation, G. Radwan area.

lying silcrete and calcrete crusts occur on the tops of some exposed karstified dolostones of El Heiz and El Hefhuf Formations.

Individual deep weathering profile, ferricrete unit, ranges from extensive sheet as in G. Radwan and Sandstone Hill to discrete lenticular or rounded masses capping isolated cone-hills and ridges within the depression (Figs. 1, 3 and 4). The ferricrete profile, 6 to 16 m thick, consists of three main horizons corresponding to those of the typical laterite profile (Pl. 1e and Fig. 5). These are: a) an upper hard cap, sandy in composition and include abundant ferruginated plant remains, cellular organic structure (Pl. 1f) and goethite coatings and encrustation. These materials grade downwards into the underlying horizon, b) varicoloured, breccia (illuvial) horizon, consisting of highly ferruginated and silicified breccia fragments embedded in a matrix rich in iron sesquioxides and kaolinitic clays (Pl. 2a). Goethite coatings and glaebules, crustified banded, cockade, nodular and pisolitic textures are common, and c) a lower C horizon of weathered rocks which may still retain the original bedding nature and sedimentary structures of the parental rocks. The contact with the successive illuvial horizon is gradational, the yellow and white colours of the parental rocks grade to brown and black. The parental rocks pass into separated blocks, and randomly oriented boulders and cobbles that are highly ferruginated and silicified. The altered blocks have been shifted slightly relative to one another and still retain the original bedding nature. Concentric pink to red layers or "Liesegang rings" are commonly developed along the fractures, bedding planes and capillary spaces of the parent rocks. Such concentric layers indicate rhythmic precipitation of iron sesquioxides from diffusion solutions.

PLATE 1

a: An aerial photograph showing the northeastern part of the A-A' master fault associated with a group of alternating anticlines and synclines on both sides of the fault. b: Aligned karst cone-hills of the eastern plateau of El Bahariya depression. c: A panoramic view showing the high-lying ferricrete duricrust (F), capping flat-topped dissected ridge, central part of the study area. d: Ferricrete duricrust (F) overlying the karstified carbonate of the Naqb Formation (Nq), Naqb El Harra, Bh = Bahariya Formation. e: A complete ferricrete profile showing the upper indurated horizon (A), middle breccia horizon (B) and the parent Bahariya Formation (C). f: Internal cellular structure of the plant remains of the A horizon with cell interiors filled with goethite (G) and elongated tissues replaced by chalcedony (ch) (Polished section, Ordinary light).



The upper most sandy (A) horizon is commonly stripped away to expose the underlying brecciated and pisolitic materials. In a few localized occurrences, ferricrete cap is not associated with deep weathering profile, but rather consists of ferruginated sandstone and quartzite.

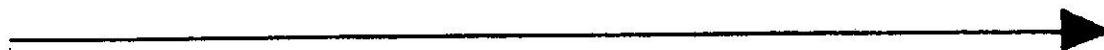
The observed C, B and A horizons of the high-lying ferricrete and their gradational contacts indicate *in situ* accumulation of iron sesquioxides and clays during the deep weathering processes. The iron of this ferricrete appears to be derived from above through the weathering of the formerly exposed iron bearing Cretaceous and Eocene rocks (ferruginous sandstone, shale, clay, ironstone and dolostone) during the continuous lowering of the relief and vadose zone with time. The abundant distribution of plant remains and organic debris in the upper A horizon reveals that, the weathering processes have been generated under vegetation cover. The role of organic activities during the pedogenesis is also evidenced by the occurrence of pyrite framboids. Under cold wet climate, decay of vegetal debris is very slow and accumulation horizon of raw organic matter occurs at the surface. It is formed of vegetal debris which is slowly degrading and which release soluble organic compounds, liable to complex the metallic cations to carry them toward deeper layer (Saxby, 1976). Under the influence of very acid organic compounds, all the mineral matter released near the surface is leached downward and eventually accumulated in the B (illuvial) horizon (Lelong *et al.*, 1976). Thus, the concentration of iron in the B horizon of the present ferricrete profile can be attributed to illuviation processes during the pedogenesis. The iron oxides and hydroxides in the ferricrete are usually linked with kaolinitic clays as yellow or red ochers indicating deposition from suspension or occur as coatings, colloform concretions, crustified layers or pisolites which suggest precipitation from supersaturated or colloidal pore soil solution. With regard to the age of the high-lying duricrusts, it must be younger than the Eocene uplifting and probably formed during the tropical humid condition of the Oligocene time (Bown and Kraus, 1988) with deposition of equivalent fluvial deposits (Qatrani Fm.) northwards of El Bahariya depression. The induration of the ferricrete deposits through dewatering, pedogenesis, crystallization and cementation processes indicates that, the erosion cycle has reached its senile stage under arid to semiarid paleoclimate. The idea that the ferruginization of the Cenomanian sandstones of El Heiz area has been developed between the Cenomanian and pre-Middle Eocene time, during the Cretaceous-Tertiary transition (Agthe, 1985 and Mücke and Agthe, 1988), can not be accepted because of the following: a) the high-lying duricrusts are of accordant summits

and cover the exposed Cenomanian, Campanian and Middle Eocene rocks, and b) there is no field evidence suggesting the preservation of these duricrusts under Eocene or older rocks. The upper Cretaceous marine sequences (El Heiz and El Hefhuf Formations) did not preserve any type of fossilized duricrusts. Furthermore, these authors did not differentiate between the original ironstone bands which encountered within the Cenomanian Bahariya Formation and the recorded high-lying and low-lying duricrusts, therefore their proposed model is invalid. The present observations also disagree with the replacement model by hydrothermal solutions, coming from unknown depth, and proposed to be related to the Oligocene volcanicity (Amer, 1968 and 1973; Basta and Amer, 1969 a,b, c and d; Awadallah *et al.*, 1984 a and b and Shaalan *et al.*, 1984). All over the Bahariya depression, there is no obvious field relation between the basalts and any type of the recognized duricrusts. The exposed volcanic rocks are spheroidally weathered and highly lateritized. The summits of the basalt caps and basaltic cone hills have nearly the same altitudes of the high-lying duricrusts.

b. Low-Lying Ferricretes

These duricrusts are developed on characteristic terrace-like features (benches), demarcating breaks within the scarp and hillside slope profiles or cover pediments and floor of the depression.

The bench-like ferricretes, 1 to 2 m thick, lie nearly at the same altitude ranging between 255-260 m a.m.s.l. The main mineralogical and textural characters of the different horizons of this ferricrete profile are shown in Figures 6 and 7. The host sediments are either mudstone, or sandstone overlying impermeable shales.



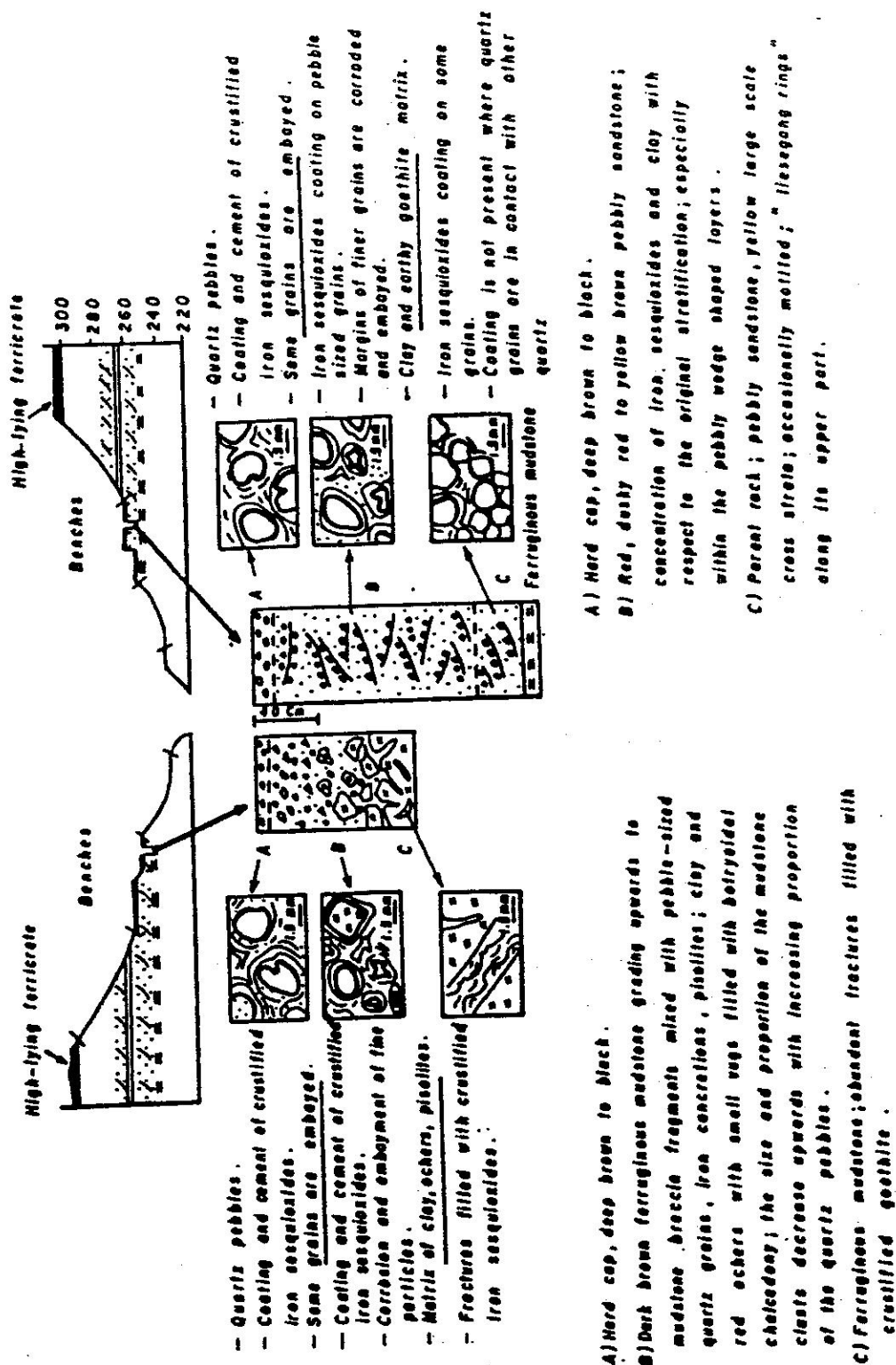


Figure 6: Summary diagram of ferricrete profiles (bench-like type), southern part of El Heiz area.

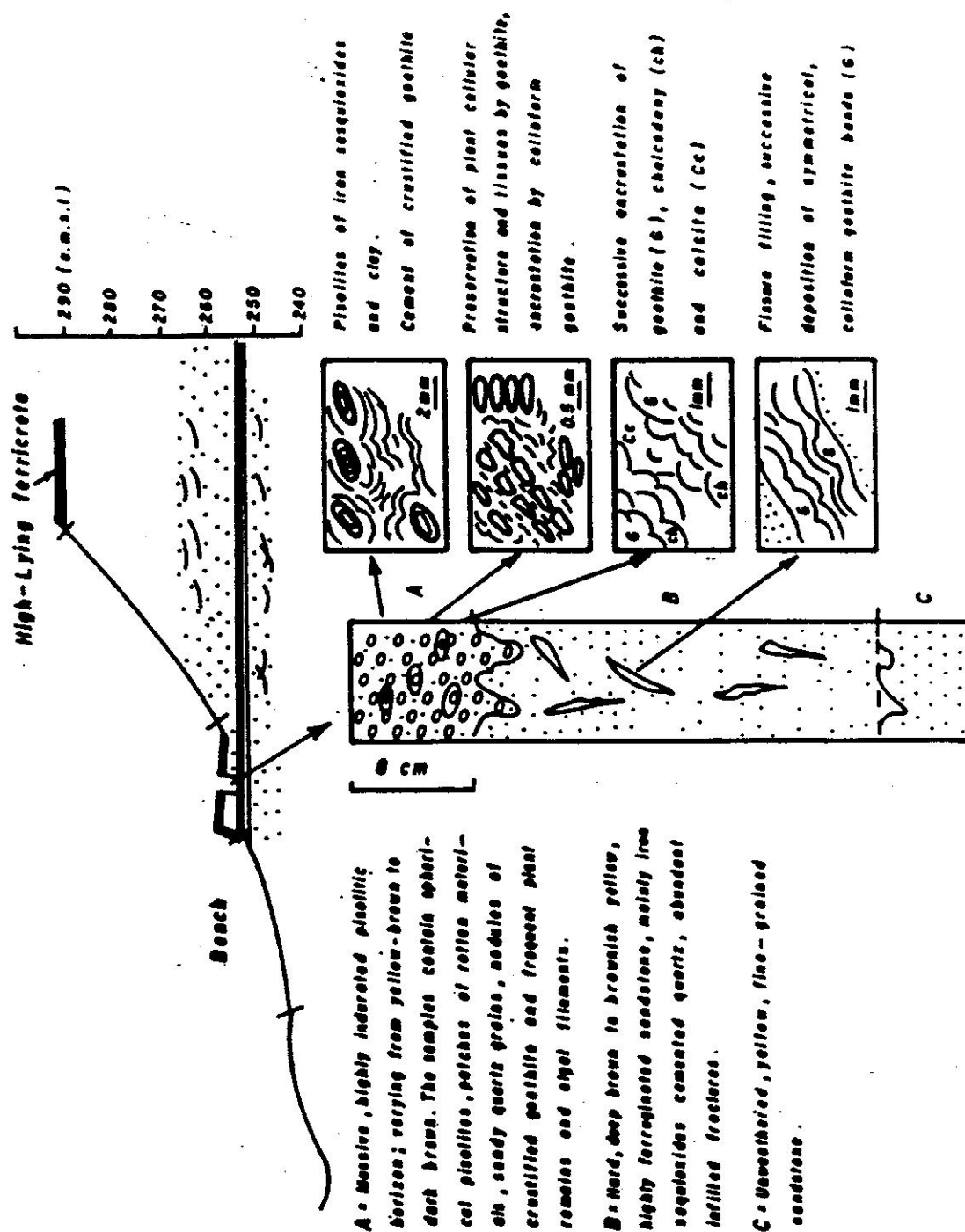


Figure 7: Summary diagram of ferricrete profile (bench-like type), G. Radwan area.

The development of the pediment ferricrete crust appears to be controlled by the lithology of the country rocks as it often overlies altered glauconitic sandstones. The ferricrete crust and the underlying rocks form small scale weathering profile similar to that described by Parron and Nahon (1980) (Pl. 2b). A complete profile of this ferricrete type can be described as follows:

Zone or

horizon	thickness	Characteristics
hard cap	6 cm	ferruginous mudstone rich in ferruginated plant remains, desiccation cracks are common (Pl. 2b,c).
Transi- tional/ mottled zone	15-20 cm	indurated ferruginous sandstone, red to dusky red with mottling effect, grading downward into unweathered rocks (Pl. 2b). The glauconite grains are completely altered into goethite mixed with clay. Dark goethite concretions and crustified bands of goethite and manganese oxide present in the upper part of this horizon. Barite cement is not uncommon.
parent rock		yellow to greenish yellow glauconitic sandstone.

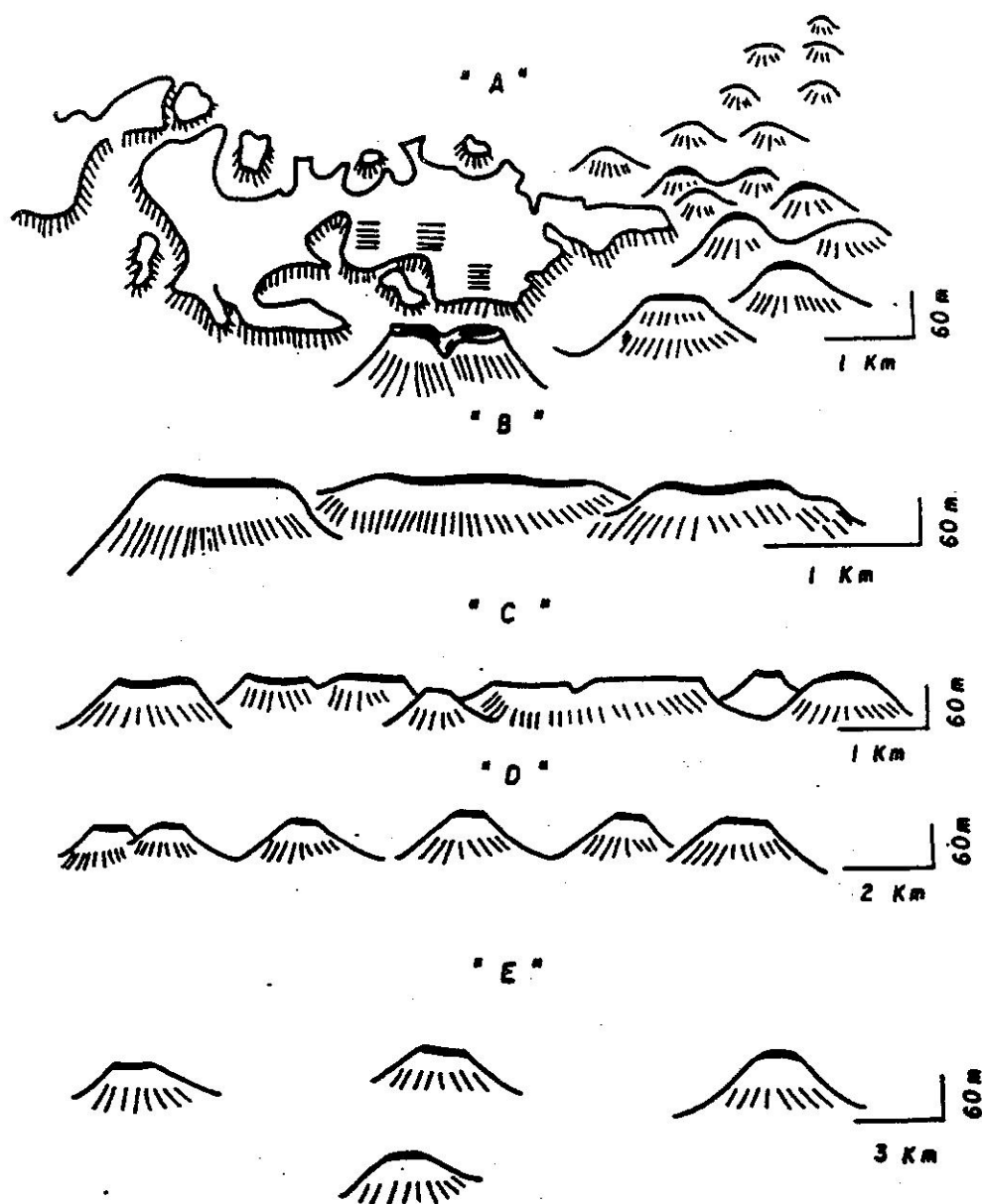
The upper hard cap of this profile is usually stripped away exposing the underlying mottled horizon. In other places, crustified bands and concretions of goethite and manganese oxides together with ferruginated plant remains and algal filaments are commonly accumulated in small drainage dells on pediment slopes. The maximum thickness of these materials, up to 40 cm, is recorded in the proximity of drainage depressions. This ferricrete crust does not show any obvious relation with the underlying rocks.

c. Contemporary (Younger) Erosion Surface and Etchplains

The floor of El Bahariya depression, 175-225 m a.m.s.l., can be regarded as the younger (lower) erosion surface of this area (S2, Fig. 4). The rocks of the Bahariya Formation which constitute this surface have been exposed to view of erosion and hence in sence, erosion surface. This surface is characterized by generally undulated or uneven relief unlike the general flat high-lying lateritic surface (S1, Fig. 4). Conspicuous erosional residuals stand on this lower surface. They are represented by large scale inselbergs such as

G. Mandisha, G. Maysera, G. Ghorabi, and G. El Hefhuf in the northern part of the depression and numerous number of smaller duricrusted interfluves in El Heiz area (Pl. 2d). Duricrusted or unduricrusted cone-hills are also left in front of the main scarps as G. El Dist, G. El Maghrafa, among others. G. Mandisha, G. El Maysera and the northern part of G. El Hefhuf are capped by hard resistant sheets of spheroidally weathered and lateritized basalt, while the southern part of G. El Hefhuf is mantled by silcrete and ferricrete with residual karst cone-hills. The occurrence of these erosional residuals within the depression is in turn a good indication of relief inversion of the surrounding plateau and the old (higher) erosion surface. The lack of any evidence suggesting that, the high-lying erosion surface (S1) have been tectonically uplifted after its formation and the development of the classical hillside slope elements argue for the role of etching and stripping of this surface, together with slope retreat, in the formation of the duricrusted erosional residuals and the lower (younger) erosion surface (S2). The formation of lower surface from the weathering profile of older surface is described as etchplanation (Wayland, 1934) and the related processes are called etching. Based on the classifications of Thomas (1955) and Faniran and Jeje (1983), different evolutionary types of etchplains can be recognized in El Bahariya depression. These are : a) partially dissected lateritized plains, b) dissected and partially stripped etchplain and, c) dominantly stripped etchplain.

Partially Dissected Lateritized Plains: This feature is represented by the upper duricrusted surface of large scale interfluves as G. Radwan and Sandstone Hill which appear to be gradually detached from the plateau (Figs. 1, 3 and 8A). These duricrusted plains are characterized by the following: 1) the lateritized plain of G. Radwan covers an area of about 2 x 12 km, while that of the Sandstone Hill, covers about 4 x 18 km, 2) they represent the water divide of the surrounding low lands; 3) they are characterized by narrow and shallow dendritic, subparallel and pinnate drainage patterns and may also be dissected by deep narrow gorges guided by the main structural trends of these two areas, 4) the uppermost surfaces of these plains are gently undulated or nearly flat, 270-300 m., upon which some conspicuous residual hills of ferricrete are scattered, up to 360 m, 5) along their outer boundaries, they are commonly dissected into isolated duricrusted cone-hills of accordant summits, and 6) values of drainage density (1:20,000 aerial photographs) average 12 in G. Radwan and 9 in Sandstone Hill, values of stream frequency (1: 20,000 aerial photographs) average 41 and 30 in these areas, respectively.



(A) Dissected lateritized plain; (B) Elongated ridge; (C) Partially dissected ridge; (D) Aligned, connected cone hills; (E) Widely spaced cone hills.

Figure 8: Schematic representation of the different duricrusted landforms of the study area. A = dissected lateritized plain, B = elongated ridge; C = partially dissected ridge; D = aligned, connected cone hills, E = widely spaced cone hills.

Dissected and Partially Stripped Etchplain: The dissected high-lying duricrusts which cover the residual cone-hills in the area between G. Radwan and Sandstone Hill can be described as partially stripped etchplain, resulted from the dissection of a former continuous lateritized plain (Figs. 1,3 and 8 B-E). The hills of this area, rising from 50 to 70 m above the surrounding lowlands and consist of nearly horizontal beds of the Bahariya Formation, are covered by ferricrete crusts of accordant summits (Pl. 2e). The height of these hills depends upon the elevations of the surrounding lowlands, as the higher hills occur above areas of low relief and the less elevated ones occur above areas of high relief. Less abundant unduricrusted hills are also present. The hills occur singular or in clusters and oriented chains. They are of symmetrical conical shapes with circular or elliptical outlines. However, some of which are asymmetrical. The latter are widely distributed along the flanks of local folds. The clustered hills are separated from each other by deep V-shaped valleys or very short pediments, the position of which are determined by the major intersecting faults and the associated fracture sets. The widely spaced hills are smaller in diameter than the grouped hills and usually separated from each other by vast dissected pediment. The oriented hill chains trend NE-SW, NW-SE, N-S and E-W. This leads to the inference that their arrangement is intimately related to structural control. Flat-topped and duricrusted ridges, often less than 7 km long, are also present (Fig. 8 B and C). They are usually divided into hill chains, having the same trends of the aligned cone-hills. Further dissection of these ridges result in the formation of closely spaced and isolated hills (Fig. 8C and D). Ultimately, the isolated hills are highly destroyed and coalescence of individual pediments gives an extensive (floor) pediplain.

Destruction and stripping of the duricrust cap of these relict landforms are indicated by the occurrence of very small hillocks of ferricrete rubbles above its uppermost surfaces and gradual fragmentation and removal of the uppermost two horizons of the ferricrete profile. Cavitation of the weathered rocks occurring beneath the hard cap results in the formation of large hollows and gradual collapsing of the duricrust cap. This led to the formation of ferricrete boulders, which may undergo further breakdown into rubble, and subsequently into pisolitic gravel, which may be washed across the pediment. Separated blocks and boulders of ferricrete are found on the tops of the unduricrusted hills. Accordingly, the summits of these hills may represent an evolutionary stage of stripping of the high-lying duricrust.

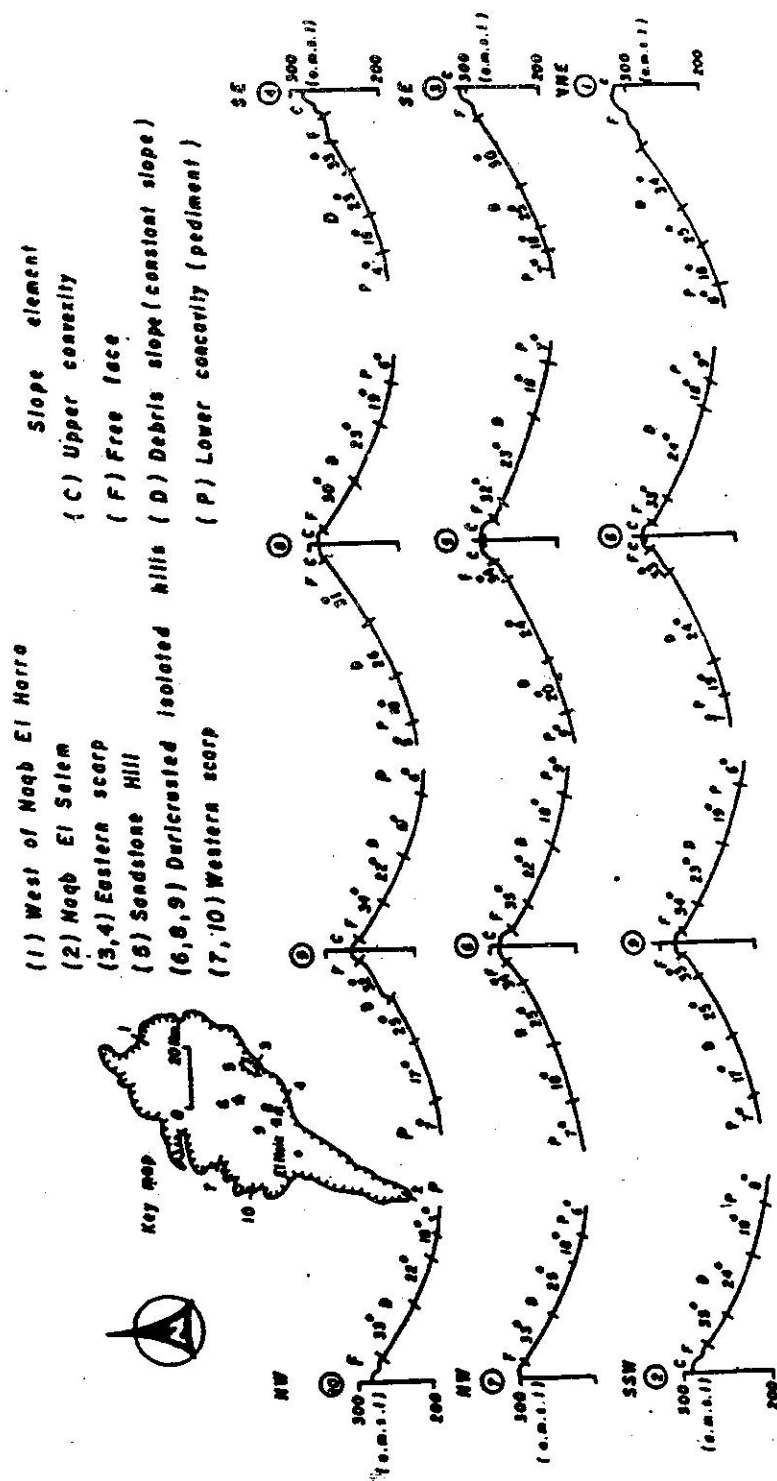


Figure 9: Representative slope profiles of the main scarps and duricrusted isolated hills of El Bahariya depression. 1 = west of Naqb El Harra; 2 = Naqb El Salem; 3,4 = Eastern scarp; 5 = Sandstone Hill; 6,8,9 = duricrusted isolated hills; 7,10 = Western scarp; C = upper convexity; F = Free face; D = debris (constant) slope; P = Lower concavity (pediment).

feature) also indicate subsequent incision of rivers leaving the former lateritized lowlands as terraces above the new level of the rivers.

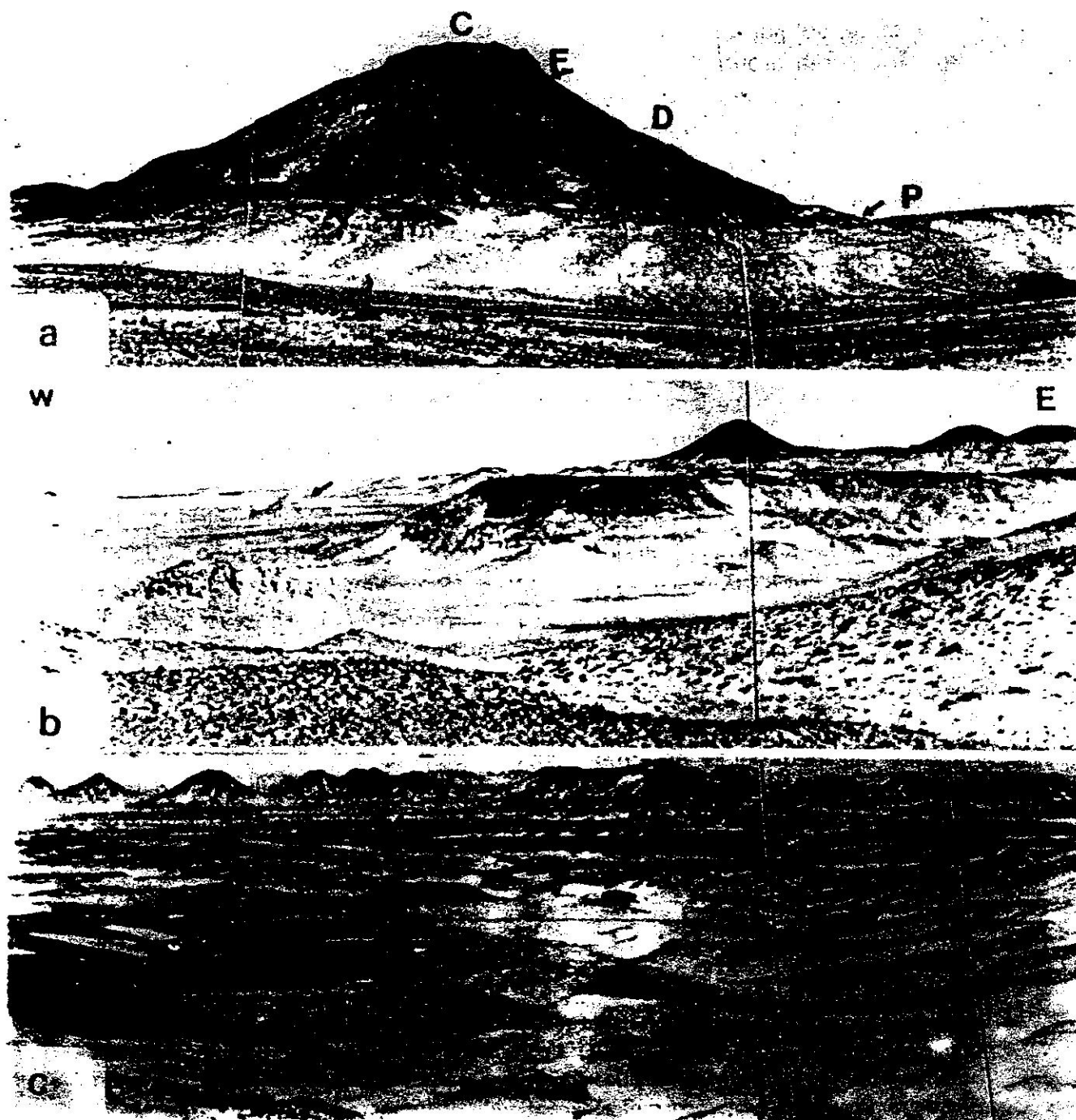
The junction between the debris slope and the surrounding pediments is either abrupt, indicating a sharp break of slope (kinck) between the slope of the hills and the surrounding footslope, or gradational due to accumulation of talus and scree around the hills. The pediments are commonly covered by either lateritic boulders and gravels or thin veneer of ferricrete. In some places, the pediments are mantled by alluvial veneer which is usually patchy but may mask completely the exposed solid rocks. In the lower parts of the pediments, the alluvial cover tends to become more continuous and thicker. The pediments are often breached by dry streams which form incised courses. These streams may extend into broad valleys, 100 m to 3 km wide, forming pediment embayments which may grow towards each other and coalesce to give pediment passes (Pl. 3b,c). The incised valleys are structurally controlled as they often develop along lines of weakness. The floors of these wadis, which delimit the base level of erosion, elev. 150-175 m, are mostly flat and usually covered by blown sand. Some of these wadis include isolated unduricrusted cone-hills (Pl. 3b).

The typical low-lying duricrust of the equatorial regions is related to the destruction of the high-lying duricrust in addition to *in situ* lateritization during alternating humid periods (Du Preez, 1949 a ; Sivarojasingham, *et al.*, 1962; De Swardt, 1964; Maignien, 1966 and Thomas, 1974). Thomas (*op cit.*) concluded that, the lower laterite may result in part by the same processes that are responsible for the formation of the older crust. Du Preez (1949 a) related the lowland laterite to pediplanation processes. The presence of knicks between the pediments and the constant slopes, the dissection of the pediments and the associated duricrust by younger small valleys, and the formation of pediment embayments and passes argue for the role of stream

PLATE 3

a : A close up view of duricrusted isolated cone-hill showing the four main slope elements i.e., upper convexity (C); cliff or free face (F); debris slope (D) and pediment (P). **b :** Pediment embayments. The incised wadis include some small isolated cone-hills (arrows). **c :** Pediment passes resulted from coalescence of pediment embayments.

Plate 3



and sheet flood actions in the formation of these pediments and indicate change in the climatic conditions during the recession of the slope. On the other hand, the presence of ferruginous mudstone layers on the upper part of the present pediment ferricrete suggests deposition from suspension of stream and sheet floods after a period of sudden and heavy rainfall, with oxidation and chemical breakdown of the exposed glauconite bearing rocks during the lowering of the water table. The accumulation of crustified iron and manganese sesquioxides and the associated plant remains within the small drainage dells may also suggest accumulation from stream load sediments or land derived soils carried in suspension.

Dominantly Stripped Etchplain: The floor in the northeastern part of El Bahariya depression, east of Ain Gafra and G. El Hefhuf is highly undulated, as local relief varies from about 150 to 225 m. The exposed fresh rocks form broad convex domes or rounded hummocks. In the area between El Heiz and Naqb El Selem, the coalescence of the pediments of the eastern and western main scarps gives an extensive pediplain, covered by salt lakes, brushes and remnants of playa deposits. These two areas represent an advanced stage of denudation and stripping of the surficial high-lying duricrusts and the underlying regoliths, aided by continuous slope retreat and pedimentation. Thus, they can be correlated with the dominantly stripped etchplains of Thomas (1965) and Faniran and Jeje (1983).

DISCUSSION AND CONCLUSIONS

The landform evolution and the sculpturing of El Bahariya depression in relation to the development of the recognized surficial duricrusts are summarized in Figure 10. Two main erosion surfaces, manifested by two main types of surficial duricrusts, are recorded. The detection of these surfaces is based upon the following : a) the presence of two types of surficial duricrusts, a high-lying type with accordant summits representing an old erosion surface and a low-lying type representing a younger (lower) erosion surface (Du Preez, 1949 b and Faniran and Jeje, 1983) and b) the separation of the high-lying duricrust from the lower lands and the related duricrusts by scarps and slopes with the well known four hillslope elements. The old erosion surface was developed over different types of rock formations and possesses very low relief with local highs and lows.

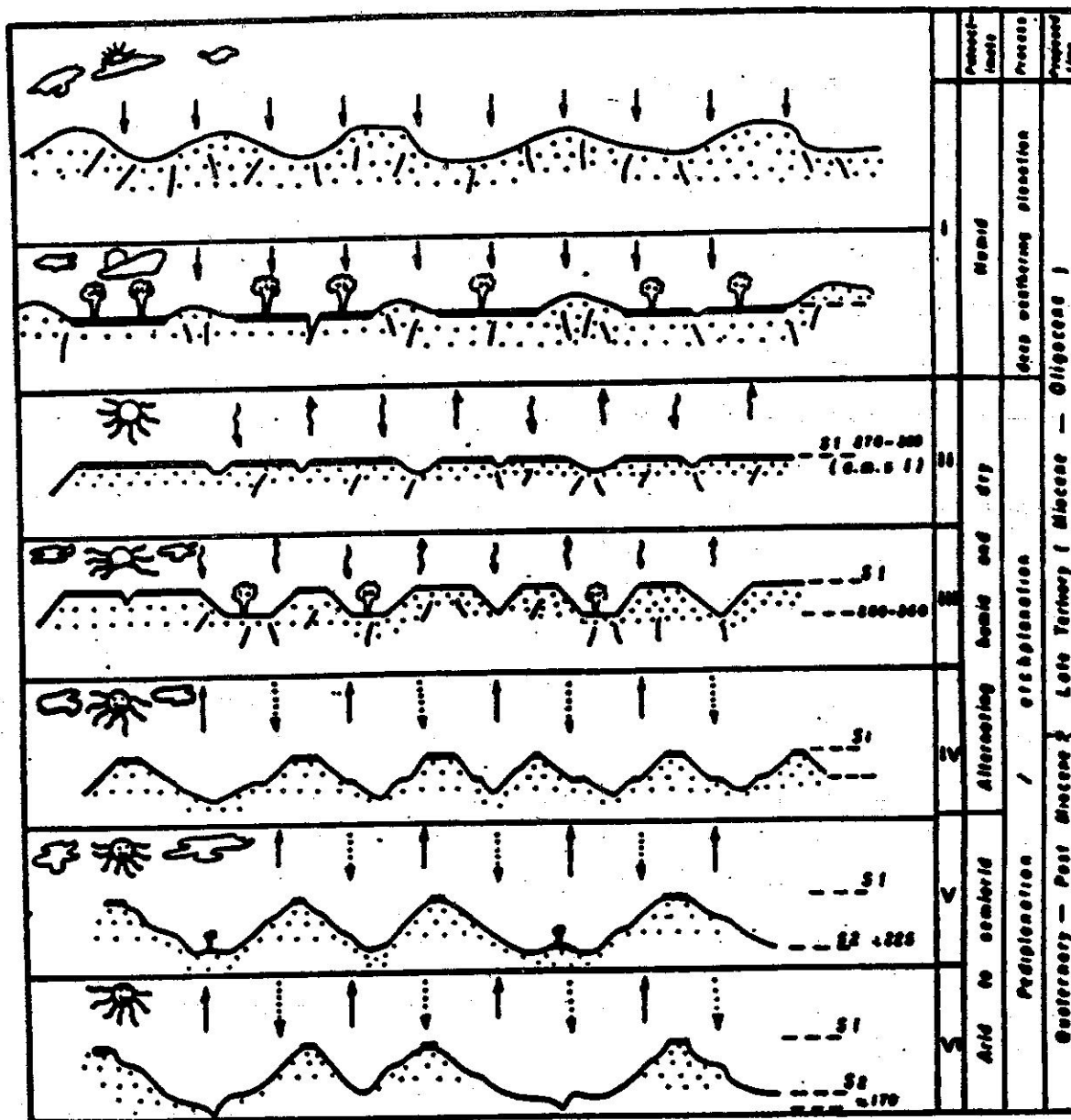


Fig. 10: Landform evolution and development of ferricrete duricrusts, El Bahariya depression, Western Desert, Egypt.

- I Uplifting, intersected structural lineaments, increase in permeability and intensive rainfall with deep weathering processes resulting in general lowering of the landscape, karstification of the exposed carbonates and lateritization; creation of an old lateritized erosion surface (high-lying duricrust).
- II more arid condition, maturation of the lateritization and development of continuous hard sheet of ferricrete during evaporation and lithification processes, beginning of river incision with gradual stripping of regoliths, development of wide interfluvies.
- III continuous incision and deepening of rivers, stripping of regoliths, slope and scarp retreat, gradual consumption of the interfluvies; downward migration of watertable; basal sapping; breaks of slopes; *in situ* lateritization on the resulted lowlands during periods of basal level stability (formation of bench-like ferricrete); continuous karstification of the carbonate rocks of the surrounding plateau, evaporation and wind erosion during arid periods.
- IV continuous deepening of rivers, widening of the valleys through destruction of high-lying and bench-like duricrusts; breaks of slopes; stripping of regoliths; slope and scarp retreat; continuous karstification of the exposed carbonates; wind erosion during arid periods.
- V continuous stripping of regoliths, slope and scarp retreat; pedimentation and pavementation; coalescence of pediments (formation of pediplains); development of thin veneer of ferricrete on the resulted pediments; evaporation and wind erosion during arid periods.
- VI predominant wind erosion, pediments are lowered and partially concealed by occasional alternation of sheet and stream flood actions forming "peripediment"; playa deposits; formation of salt crusts in area of high water table level, wind deposits.

The high-lying ferricrete duricrusts represent a typical deep weathering profile of three main horizons, consisting, from top to bottom, of : an organic rich hard cap, illuvial (breccia) horizon and weathered or unweathered parent rocks. The presence of these duricrusts at nearly the same altitude, the gradational contacts between the different horizons and the development of these surficial duricrusts above typical humid residual landforms indicate *in situ* lateritization and residual concentration through the general lowering of the exposed rocks under intensive humid conditions.

After the regression of the Eocene sea, El Bahariya area was subjected to tensional adjustment during the rejuvenation of the old structural elements and the whole area was dissected by faults and associated fracture sets. The general relief was characterized by local highs and lows. The area witnessed an intensive humid period during which deep weathering processes involving karstification resulted in the general lowering of the landscape, lateritization and formation of typical deep weathering profile (probably during Oligocene-Miocene ? time). The development of the deep weathering (duricrust) profile on the lowlands during general lowering of the landscape is in accordance with the low relief concept of duricrusting of Woolnough (1927).

The main humid period was succeeded by more arid conditions that led to : a) the maturation of the lateritization processes and the induration of the soil materials, through pedogenesis, lithification, cementation, recrystallization, and development of continuous hard sheet, b) incision of rivers with gradual dissection and etching of the duricrust sheet through, the stripping of regolith by slope and scarp retreat and, c) the development of wide interfluves and continuous backwearing of the slope with gradual consumption of the duricrust cap. The presence of the high-lying duricrusts with nearly the same thickness and altitude all over the small as well as the large isolated cone hills and ridges, and the presence of talus and scree from the duricrust fragments along the slopes of the residual landforms indicate the destruction of this duricrust sheet after its formation.

After the incision of rivers and dissection of the hard duricrust sheet, El Bahariya depression was subjected to alternating humid and arid periods resulting in : a) continuous stripping of the regoliths by slope and scarp retreat. The continuation of the retreat of slope led to the further consumption of the wide interfluves and the development of large duricrusted inselbergs and ridges. The area of G. Radwan represents partially dissected lateritized plain, while the summits of the residual landforms within the depression represent an advanced stage of dissection and stripping of the previously continuous

hard sheet. The dissection of the hard sheet and the distribution of the residual landforms appear to be controlled by the NE, NW, N-S and E-W faults and associated fracture sets, b) development of the bench-like ferricrete which represents *in situ* lateritization on the resulted lowlands during periods of basal level stability. In subsequent humid periods, the already formed ferricrete crust was dissected, leaving the characteristic bench (terrace-like) features on the hillside slope. Contemporaneously, the exposed carbonates of the surrounding plateau have been subjected to continuous karstification processes, c) development of pediments by stream and sheet flood actions during the humid periods and, d) removal of the loose sands that resulted from the continuous stripping of the regoliths.

The alternating humid and arid periods were terminated by arid to semi-arid conditions with occasional rainstorms. These conditions led to: a) continuous stripping of regoliths by slope and scarp retreat resulting in the gradual consumption of the interfluves and formation of small duricrusted cone-hills and ridges, b) development of vast pediments, c) coalescence of the resulted pediments and formation of a characteristic pediplain, d) development of thin veneer of the low-lying ferricrete on the resulted pediments, e) formation of peripediments, f) evaporation and deposition of playa deposits and salt crusts and g) wind abrasion and deposition.

The present study revealed that, the landforms of El-Bahariya depression and the related surficial duricrusts were formed by multiple cycles of deep weathering processes involving lateritization, etchplanation, karstification, pedimentation, pedogenesis and diagenesis under certain paleotopographic and paleoclimatic conditions. The existence and correlation of the recorded erosion surfaces and the associated duricrust profiles of the study area with the surrounding areas should be considered, particularly the recent recognition of similar erosion levels in El Bahariya - El Farafra stretch (Abu Khadra *et al.*, 1987) and Wadi Sannour, East of Nile Valley (Philip *et al.*, 1989).

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تكوين رواسب تربة حديدية «فركريت» وعلاقتها بالتطور الجيومورفولوجي لمنطقة الحيز بالواحات البحرية، الصحراء الغربية، مصر

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تهدف هذه الدراسة إلى إلقاء الضوء على طبيعة وطريقة تكوين الرسوبيات الحديدية المتواجدة في منطقة الحيز بمنخفض الواحات البحرية وكذلك توضيح العلاقة بين تكوين هذه الرسوبيات والتاريخ المورفولوجي للمنخفض. وقد أثبتت الدراسة أن المنطقة تحتوي على سطح تعرية رئيسين كما استنتجت أن الرواسب الحديدية تمثل قشرة سطحية طده من رواسب تربة قديمة تكونت بفعل عوامل تعرية على سطح التعرية القديم والذي من المرجح أن يعود عمره إلى عصر الأوليجوسين - ميوسين (٢) وتغطى هذه القشرة بقايا الارتفاعات وهضاب مخروطية الشكل. ومن دراسة هذه القشرة السطحية يمكن استنتاج العوامل المناخية والتغيرات الكيميائية والبيولوجية المختلفة والتي صاحبت عمليات التعرية القديمة وقد تم الاستدلال على وجود قشرة حديدية أخرى مكونة على سطح التعرية الأحدث والممثل بآرضية المنخفض الرئيسي للواحات البحرية. ومن تتبع الخواص الجيومورفولوجية لهذه القشرات السطحية وكذلك تطور المظاهر الجيومورفولوجية المختلفة في منطقة الحيز ومنخفض الواحات البحرية يمكن استنتاج التاريخ الجيومورفولوجي للمنطقة وأصل تكوين منخفض الواحات البحرية وعلاقة هذا التطور الجيومورفولوجي بتكوين القشرات الحديدية المختلفة.